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TESTS AND GUIDELINES FOR DEEP DIELECTRIC CHARGING IN SPACECRAFT

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Abstract

Spacecraft electric insulators are sources of spacecraft anomalies especially as the spacecraft experiences the radiation belts around Earth. Evidence indicates that anomalies that occur in the electron radiation belts are caused by spontaneous discharges of irradiated insulation such as cables and circuit boards. The few existing ground tests find pulses on 50 ohm oscilloscopes up to 150 V from typical cables, and 2 kV from specialized exposed antenna transmission lines and circuit boards. Guidelines are needed to predict how an untested sample will spontaneously discharge, or how a sample will respond if changes are made to it or to the radiation environment. Experimental results from a variety of spacecraft insulators will form the basis for developing guidelines and predictions for discharge pulse characterization. This paper summarizes the current results of this ongoing study program.

INTRODUCTION

Evidence indicates that a significant proportion of spacecraft anomalies that occur in the electron radiation belts are caused by discharges on irradiated cables and circuit boards [1-6]. The few existing ground tests find pulses up to 150 V on typical cables, and 2 kV on specialized exposed antenna transmission lines and circuit boards [6,7]. Further guidelines are needed to tell one how an untested sample will respond, or how a tested sample will respond if small changes are made to it or to the radiation environment. Using reasonable theories [8,9], extrapolation of test data to slightly changed designs sometimes predicts dramatically changed pulsing response. Such theories will be tested and will guide the investigation to provide designs that don't pulse and to provide warnings for designs that are likely to be a serious problem. Although theory helps, experimental results form the core of the investigation.

The investigation will develop quantitative data and design guidelines for charging and discharging of spacecraft insulators under high energy electron irradiation typical of Earth's and Jupiter's magnetospheres. Existing published and unpublished test results will be summarized and new data will be obtained for yet-to-be-tested structures. Design rules will be developed to predict the effects of changing both the cable and detailed structure including: insulation thickness, wire size, insulation pinholes, applied voltage, over-wrap thickness, shield thickness, wire spacing, leaky coatings, and leaky dielectrics. Electrons from 20 keV through 2 MeV will be used for testing. Mitigation techniques to prevent discharges are theoretically available and will be developed and proof-tested. Quantitative measurement of pulse magnitudes and frequency of occurrence [10] will be tabulated so that one may design around a pulsing cable if one so desires. Radiation test methods will be formalized for more quickly evaluating future materials and cables.

Future integrated circuits will operate with voltages as low as one volt and will therefore be more sensitive to events produced by charging phenomena. A major source of internal charging and discharging on spacecraft is the hundreds, perhaps thousands, of feet of cabling that is shielded by no more than the spacecraft's thermal blankets, by antennas, and by lightly shielded circuit boards. This work will therefore address the issue of pulse size generated near sensitive circuits.

In 1957 Bernhard Gross reported a scientific investigation of charging and discharging of electron irradiated borosilicate glass [11]. He noted that high electric fields were generated but their magnitude was not estimated. He observed that a sharp object placed on the surface would sometimes cause the instantaneous appearance of a flash of light with a discharge tree which exited the glass where the object touched the surface. There was no discussion about how the tree formed, or of the magnitude of current in the flash. At that time the phenomena were generally thought to be interesting, fun to replicate, known to occur in plexiglass and borosilicate glass, but not of broad engineering importance. At that time the interesting effects in irradiated insulators were "how much charge they could capture and store, and at what depth would the irradiating electrons stop."

A physical model of the breakdown process could be used to predict the responses of components that are different than those already tested. For example: if electrons blowoff a highly charged surface, they are capable of impacting and charging a nearby surface to a nearly identical high voltage (depending on relative capacitances). The existing spacecraft design guidelines do not address this and other issues. The early physical models had been used only to rationalize the observations in early experiments [12-16]. The existing guidelines are essentially a compendium of a small fraction of the currently available test data. The actual physics of the charging and the discharging processes have not been used to broaden the spacecraft design guidelines.

It had been mentioned in the literature that the object which punches through or blows off is the plasma streamer [17]. But the implications of this subtle distinction were not widely recognized. It means that it is the motion of dense plasma that controls the current flow in the discharge. As the dense plasma inside the solid escapes from the surface and expands into the vacuum, it passes through several regimes of conductivity. Inside the dense confined channel the plasma instantly collapses the previous electrostatic field and the plasma oscillates with plasma frequency well above the microwave spectrum. The previous electric field energy density can cause only a few percent of the gas molecules to be ionized. The gas/plasma is dense, but not highly ionized. As the plasma expands into the vacuum space, the gas pressure falls and the neutrals begin to become involved in a Townsend/Paschen discharge provided that the electric field in the vacuum is high enough. Unbeknownst to most experimenters, it is the Townsend/Paschen discharge outside the insulator that was investigated in most cable and solar blanket testing [18].

Why is the theory of the discharge important? A number of guidelines can be proposed based upon the streamer and Paschen discharge process. Levy found that this Paschen discharge could bridge between two exposed metal electrodes and short them if their applied bias was at least 50 V [18]. The electrodes provide gas atoms to indefinitely continue the arc as long as the power supply will provide the power. One therefore deduces that if a plasma streamer is formed inside the dielectric and escapes close enough to the exposed cable wires, then a permanent arc might form. Therefore exposed biased metal wire must not be in proximity to irradiated insulators, but we do not yet know "how close" is dangerous.

Another previously neglected component of the theory is important. In reviewing the literature, Frederickson found that the discharge pulse scaling laws that are based upon tests of thermal blanket materials are controlled mostly by the geometry of the vacuum chambers in which the objects were tested [6]. He finds another scaling law for a new parameter, slew rate. Slew rate is the time derivative of the current, and is sometimes called rise or fall rate. The slew rate increases with increased electric field in the vacuum because the rate of generation of free charge increases at high field during the Paschen discharge. Thermal blankets facing space produce a small electric field, and their discharges will have a reduced slew rate relative to slew rates in lab experiments. But cable bundles typical on spacecraft may have an enhanced electric field compared to vacuum tank tests of thermal blankets and therefore experience enhanced slew rates. Enhanced slew rate provides more threatening discharge pulses in sensitive electronic circuits. We lack sufficient knowledge of slew rate enhancement for cable bundles on spacecraft.

The pulses seen in lab tests on real cables can have a very complex shape not at all like those seen on thermal blankets [6]. Because pulse shapes in lab tests of thermal blanket are very repeatable, there are scaling laws for thermal blankets [13]. For cables, we have been able to provide only one important design rule: a floating wire in the bundle will dramatically increase the size and duration of the observed discharge pulse [3,16]. But, the fundamental discharge physics for cables must be the same as that for blankets, and therefore better guidelines for cables should be possible. An introduction to this possibility is provided in [6]. It is likely that the complex cable pulses are caused by the complex distribution of surface voltages on individual wire insulation within the bundles. As the wires twist among each other in the bundle, and the space electrons penetrate and stop in the bundle, one wire's insulation may be at the highest potential at a particular point in the bundle, but another wire's insulation may be most charged a few cm away. Thus, as the plasma propagates along the bundle, complex current pulses are generated on the wire conductors. Recent laboratory tests have provided significantly increased cable test data, and this data needs to be organized, assimilated, interpreted, and published.

PREVIOUS TESTING

Early testing of spacecraft cables was motivated by the need to insure that the polymeric insulation would not fail mechanically or electrically under total dose exposure [19]. Polymers were known to degrade under radiation. The degradation could turn the polymer into powder, or into severely cracked shrunken surface layers over a less damaged core polymer. In some polymers the degradation could form a more rigid or brittle structure. Formation of cracks would be associated with the loss of mass. Both cracks and powdering are associated with reduced electrical breakdown strength of the insulator, especially in those cases where the residual is more highly carbonized.

Most polymers were found to withstand 10^9 rads of ionizing radiation before their degradation became a problem [14]. Charging and pulsed-discharging of these insulators was not noted in the early tests. The charging and occasional pulsed-discharging do not leave any obvious damage in typical cable material. Only if one were carefully monitoring for the phenomena would it be seen. Most testing was performed in room air where the ionized air holds the surface potential of the insulator to negligible voltage. The discharge signals in such cables are now known to be typically 10 volts or less and 10 nanoseconds long which was difficult to capture on oscilloscopes of the time. For most applications, such discharge pulsing would be of little interest since it was so small. It was not appreciated that radiation would lead to large electric fields internal to the insulation that would, like lightning, spontaneously generate a breakdown channel through the insulation after only 10^5 rads.

An old concept held peoples' attention into the 70s, that a conductive channel would somehow evolve, perhaps by migration of ions, and as conduction increased the channel would heat up to form a channel of gas in which the breakdown would develop. In the 1960s and 1970s a few people in the high voltage insulation community learned that breakdown through a high-voltage insulator was always preceded by the formation of a narrow streamer channel of plasma that passed entirely through the material from electrode to electrode. The high-speed photographs taken by experimenters such as Eric Forster are dramatic testimony to the importance of the streamer for initiation of full breakdown. Streamer channels that briefly formed but quenched and did not pass entirely through the insulator would not cause breakdown of the insulator. As late as 1980 it was not yet generally accepted that the physics of the plasma streamer held the key to the phenomenology of the discharge process.

Recent ground-based experimental studies have shed some new light on both the charging and discharging physics while finding discharge data that severely disagree [6] with the existing guidelines. For example, thermal blankets in large chambers produce smaller peak current and smaller slew rate than do the same thermal blankets in small chambers. Also, covering an antenna element or circuit board with sheet insulator can dramatically increase its pulse amplitude and slew rate, and even reverse the polarity of the pulse. Continued cable tests have found interesting pulse shape phenomena.

Space-based tests have provided some data on the frequency of occurrence of pulses, [5,10] and a reinterpretation [6] of old ground tests indicates that the in-space pulses might be much smaller than predicted by existing guidelines for thermal blankets. In these tests, spacecraft cables and circuit boards were seen to pulse frequently in the high-energy electron van Allen Belts. Application of a new model of the physics of the discharge implies that a number of important issues have not been addressed in the spacecraft design guidelines. These issues are elaborated below. Beyond [5] there is little direct measurement of discharging by irradiated insulators in space.

On coaxial cables one frequently sees pulses of order one to ten volts. Occasionally pulses are as large as 50 volts when the outer jacket is thick and highly charged. In multi-wire bundles the pulses are frequently 5 to 20 peak volts, but if one of the wires is floating the pulses frequently exceed 100 volts. Pulse shapes are very variable, sometimes being unipolar but most often they are both negative- and positive-going. The complex pulse shapes are not due to ringing even though mismatched-cable ringing adds to the complexity of the pulse. The pulses themselves are bipolar, and an example with explanation is given in [6].

All previous tests were performed on nominal cables and simple boards. No attempt was made to address issues such as:

a) Effects of long evacuation, drying out to store charge better.
b) Overwrap being applied tighter or looser
c) Thicker/thinner overwrap
d) Coupling from pulses outside to inside wires
e) Effect of high voltage on adjacent wires and traces
f) Will semi-insulator coatings on individual wires attenuate pulse amplitude
g) Treat the insulator to reduce charge storage
h) Is pulsing more probable at low temperature
i) Effects of adjacent boards, etc.

APPROACHES IN THE STUDY

Much of the study is guided by models of the discharge process. These models may or may not be correct, but they explain all of the known experimental data on radiation charging/discharging [6]. The models indicate that important effects have yet to be investigated for cables and boards. An interesting outgrowth of the study might be a further confirmation, or a denial, of the models' generality. However, the primary purpose of the study is to build an empirical database to guide designers to the qualitative and quantitative features of radiation charging and discharging effects. Arguments about the physics of the models are not a focus of this investigation. The following approaches are suggested by various models.

1. Gather a typical group of spacecraft cable and board samples to cover the range of standard technologies.
2. Irradiate the samples and measure the resulting range of pulse sizes and shapes using digitizing oscilloscopes. Combine these data with an extensive set of data already in the lab that is not yet consolidated and published.
3. Construct cables to study thicker and thinner insulation. We expect thicker insulation to charge more severely and produce bigger pulses just as a floating wire is already known to do. Based on existing theory, there may be a thickness range where virtually no pulsing will be experienced, and such a guideline would be useful.
4. Test the following thesis: A discharge is initiated by a local burst of plasma-gas within the cable bundle. The electrical pulse on wires is created mostly by the process of the gas spreading inside the cable and discharging the surfaces of individual wire insulation to the (grounded) cable shield. If the thesis is true, then by impeding the spread of the gas, one impedes the pulse, and vice-versa.
5. Another cure exists for the hypothesized gas discharge mechanism. If each insulated wire in the bundle is coated with a thin but slightly conductive coating that is grounded, then the surfaces of the wires are all at ground potential. Thus the gas between the wires has no voltage to discharge, and therefore only small current pulses will develop. This will be tested by painting the cables with semiconducting paint that is connected to ground. This might form a successful cure for all pulsing by cables.
6. Some cables and boards carry > 50 volts. It has been proven by experiment [18] that the gas from a discharge of the charged insulation will evolve to short out metal electrodes carrying >50 volts. Cables/boards in which the insulation of each wire/trace is violated by pinholes will be tested to see if typical flaws in insulation are threatening above 50 volts.
7. All wiring ends at a connector or bulkhead of one sort or another. The insulation of the connector itself can charge and discharge, and will therefore be tested.
8. The exposed solder terminals of connectors can be shorted when carrying more than 50 volts and a discharge pulse occurs nearby [18]. We will test to see if semi-insulating or insulating paint prevents the short from forming.
9. We will provide theoretical and experimental data on the amount of shielding to use to protect the connector from high-energy electrons.
10. We know from previous unpublished experiments that the outer cover on cables, outside the braid, is a major source of large pulses inside. We will test several outer covers both with and without conductive overcoat.
11. A transfer function will be developed to relate the pulse on the inside of the cable to the pulse on the outside of the cable. Pulses on the outside of the cable can originate from several sources: the outer cover of the cable, insulators near the cable, ungrounded metals near the cable, etc. Each of these sources produces characteristic pulse signatures for which a transfer function can be empirically developed.
12. We will develop guidelines for the use of electric pulsers to perform non-destructive ESD system tests on cables

RESULTS

Many samples have been obtained. For example, the list of circuit board samples is shown in the appendix. Similarly large selections of connectors, thermal blankets and cables have been assembled ready for testing.

A testing chamber and electron source has been assembled and tested. It is capable of testing samples at temperatures from –50 to +100 degrees C. Data is automatically collected by a four-channel scope monitoring up to four independent samples simultaneously. The scope autonomously captures the pulses, records them to hard disk and continues monitoring.

Four circuit boards have been tested for five days under 10 to 35 keV bombardment. They are described as from NVF Co. in the appendix. It is important to have patience because samples may not pulse for extended periods. Little to no pulsing occurred for the first two days while these samples dried out in vacuum at room temperature. Presumably the conductivity due to volatile species in the samples holds down the development of high field in the insulator until the insulator outgasses. Evidence from space indicates that the outgas process continues for six months [5].

The geometry for these tests is simple. The bare insulated 50 sq. cm surface of board is bombarded by electrons causing the surface to become highly negative with respect to chamber ground. Similar experiments are discussed in Figs. 1-3,5,8,9 of [6] with this experiment being closest to Fig. 2 of [6]. The copper cladding on the reverse side of the board is bombarded only by scattered electrons and is connected through a 50 ohm signal line to ground. The pulses are measured on the signal line using fast digitizing oscilloscopes.

Typical pulses are shown in Figs. 1-5 from these four samples. The first four pulses were produced in small sample enclosures where the sample surfaces are no further than 4 cm from a ground surface. A 90% transmissive wire ground screen is between the samples and the electron beam 3 to 4 cm from the sample surfaces. Typical large pulses looked like Fig. 1. Sometimes the pulses would exhibit two or more substantial peaks as shown in Fig. 2. One might presume that such pulses indicate that the gas plasma shows fluctuations in resistance or density, or perhaps some fluctuating current flows through the plasma to the rear electrode on the sample causing a tendency for the pulse to move toward negative measured current. Several pulses were seen to fully reverse sign after an initial positive current flow, but they went off-scale because the scope was set too sensitive so they are not printed here. These reversing pulses are confirmation that sometimes the discharge plasma connects directly from the charged surface to the signal wire. Figures 3 and 4 indicate that small pulses also occur. Pulses are not of uniform magnitude and may only partially discharge a surface.

Do time integrals (charge) of pulses become larger than Fig. 1? The capacitance of the sample is approximately 100 picofarads. The voltage developed on this capacitance by 2.4 microcoulombs is 24 kV. The 30 kV beam is not capable of charging the sample far above 24 kV, so one must assume that the surface voltage has been nearly fully discharged by the pulse in Fig. 1. Only if one achieves larger surface voltage or larger sample capacitance can the pulse become larger.

Figure 5 is for sample 1 remounted so that its surfaces are everywhere at least 17 cm from a grounded metal surface. There is no screen above the sample. All of the 19 pulses from this sample arrangement showed the substantially lowered slew rate on the rising edge of the pulse. The rising slew rate in Fig. 1 is approximately 4×10^8 A/s, and in Fig. 5 is approximately 2×10^8 A/s. This result is in rough agreement with a recent proposed model, described below, for estimating pulse shapes and sizes. It indicates that the pulses will be more threatening as the charged surfaces are placed in closer proximity to elements of other circuits that are grounded.

PROPOSED MODEL FOR PULSE SHAPE

When designing a spacecraft system one often chooses to design for the worst case failure threats. For the threat of discharge pulses, the worst case occurs when the surface of the charged insulator completely and rapidly discharges. One desires a guideline by which pulses may be estimated for a wide variety of insulator geometry. While surveying data in the prior literature a crude physics model was developed.
The important physics of the discharge can be qualitatively described. A surface and/or bulk discharge tree spontaneously forms in the insulator and generates gas composed of the insulator material. The gas is slightly ionized and rapidly spreads into the vacuum. The pulse occurs when a Thompson/Paschen discharge forms in the gas under the stress of the high electric field between the insulator surface and the grounded walls. The initial leading edge of the pulse may be due to electrons alone moving from the insulator to the walls. But the vast majority of current is carried by the gas discharge which generates many more free electrons and ions. The current continues to rise as more gas evolves, becomes ionized, and spreads to discharge more of the surface. The gaseous plasma may be simulated by a time varying resistor, R, across the vacuum space.

Initially, the increasing accumulation of gas in the vacuum produces a decreasing plasma resistance to current flow, and therefore an increasing amount of current. The production of gas is initially controlled by the insulator discharge process itself. Ions and electrons from the initial gas bombard surfaces and liberate more gas. Experience indicates that the amount of gas is sufficient to carry hundreds of amperes, and at least to 100 amperes the gas is not a limiting factor. Eventually the surface becomes more than half discharged, and despite increasing amounts of gas, the electric field is so reduced that the current in the gas discharge falls rapidly.

The following parameters take part in controlling the current in the pulse:

1. Time-integrated current (charge) is controlled by surface capacitance and voltage.
2. Current slew rate, dI/dt, is controlled by electric field in the vacuum near the insulator surface, and by rate of change of gas pressure or resistance R.
3. Peak current is controlled by slew rate and the smaller linear dimension of the surface.
4. The fact that this is a diffuse gas discharge causes the internal impedance, R, of the discharge to

nearly always exceed 100 ohms. The external circuit modifies the current only when its impedance is comparable to or larger than the discharge impedance thereby modifying the electric field in the vacuum.

The primary parameter, slew rate, is set by the gas ionization process. The survey of worst pulses indicates that, slew rate has the following dependence on electric field:

1. At E=1E3 V/m the slew rate is 1E8 A/sec.
2. At E=5E4 V/m the slew rate is 1E9 A/sec.
3. At E=1E6 V/m the slew rate is 1E10 A/sec.

These data are averages over many pulses and are not precise. Accumulation of more data will be helpful. Dependence on sample material and vacuum dimensions are not yet determined but may be interesting when and if a sufficient variety of materials are investigated.

ESTIMATION OF PULSE SIZE

One might assume for square or circular samples that the pulses are shaped as isosceles triangles. Figure 5 is closest to isosceles here. Half of the pulse is linearly rising, the other half is linearly falling at a similar slew rate. Define S = slew rate, C = surface capacitance to ground, V = surface voltage to ground, Q=CV, Dt = full pulse width, and Ip = peak current. It is easy to derive for the isosceles waveform that

$$Dt = (4Q/S)^{1/2} \text{ and } Ip = (S\,Dt)/2.$$

When the oscilloscope is less than 100 ohms and the sample surface voltage exceeds 1 kV this result is a reasonable facsimile of the data in the literature and unpublished test data from many sources. For large circuit (scope) resistance one subtracts the voltage drop across the circuit from the surface voltage in order to correctly estimate electric field in the vacuum. As the vacuum electric field drops when the circuit voltage rises, the slew rate will drop, and thereby the peak current will not rise as large. The case of large circuit resistance is not considered important at this time in the development of the guideline. If circuit resistance is large, a dangerous peak voltage greatly exceeding 100 V is developed across the circuits, and for modern integrated technology the circuit is destroyed and one need not proceed any further with analysis. Instead, the pulse must be prevented.

To derive these equations one assumes that the pulse shape has equal rise time and fall time. Inspection of the results of many experiments indicates that this is not true. The rise time and fall times may differ by a factor of two or three or more. As a result of this, the value of I-peak might vary from the estimated value by 50%.

For most applications, I-peak is a critical parameter which determines whether the spacecraft suffers a problem. Addition of 50% to the estimated I-peak would be a necessary safety margin.

Inspection of Figs. 1-5 indicates that some peaks are truncated. This effect in Figs. 1-4 is thought to be due to escape of plasma/gas through the 90% transparent grounded screen above the sample surface. Escape of the gas limits the amount of gas available for the development of full discharge current. Assuming this argument to be true, one may test with grounded opaque thin metal foils in place of the screen while irradiating with higher energy electrons that penetrate the foils. This test should produce shorter and higher pulses for the same samples tested in Figs. 1-4. Such tests will be performed shortly.

In some circuits the slew rate itself is important. For example, the slew rate helps to control the extent in frequency space occupied by the pulse. If one wanted to filter the signal, then the pulses with diverse slew rates would be hardest to filter. Further review may delineate the range of slew rates experienced in testing.

Application of this predictive model finds the following general trends. For a spacecraft surface discharge to space, the threat (peak current) is small. For discharging of surface elements of spacecraft to other surface elements, the threat is moderate. For discharging of antenna insulators to antenna cables, the threat is large. For discharging inside electronic boxes, the threat is large. Inside cable bundles, a floating conductor is a large threat while typical wires are a moderate threat.

SUMMARY

1. An experimental program is proceeding to survey internal discharging phenomena inside spacecraft with typical materials subject to high radiation levels.
2. An automated electron beam system has been built to irradiate up to four simultaneous test samples in a routine manner without operator intervention. The system runs reliably hour after hour allowing one to economically study the rare events of discharging.
3. Review of existing literature finds significant data is available to tentatively provide some guidance for design purposes.
4. An initial guideline for estimating pulse size/shape is proposed.
5. The truncated pulse shape in Figs 1-4 is a new finding and may lead to better concepts for design guidelines.

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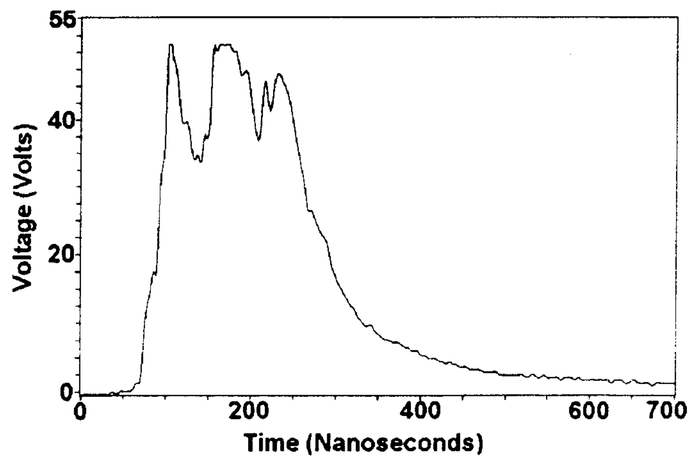

Figure 1. FR4 circuit board sample #3, 7/9/99-2.07, 30 kV beam, 1 nA/cm2, 20 db attenuation (Vx10). Peak discharge current of 10 A. Total discharge approx. 2.4 microcoulombs.

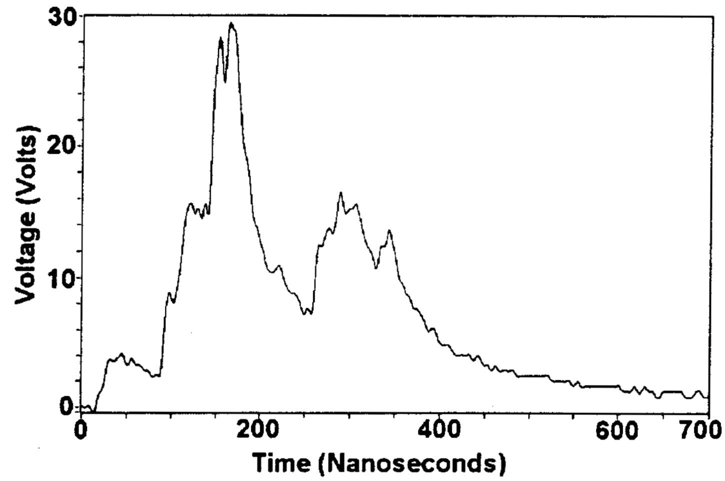

Figure 2. . FR4 circuit board sample #1, 7/12/99-4.42.30, 30 kV beam, 1 nA/cm2, 20 db attenuation (Vx10). Peak discharge current of 6 A. Total discharge approx. 1.2 microcoulombs.

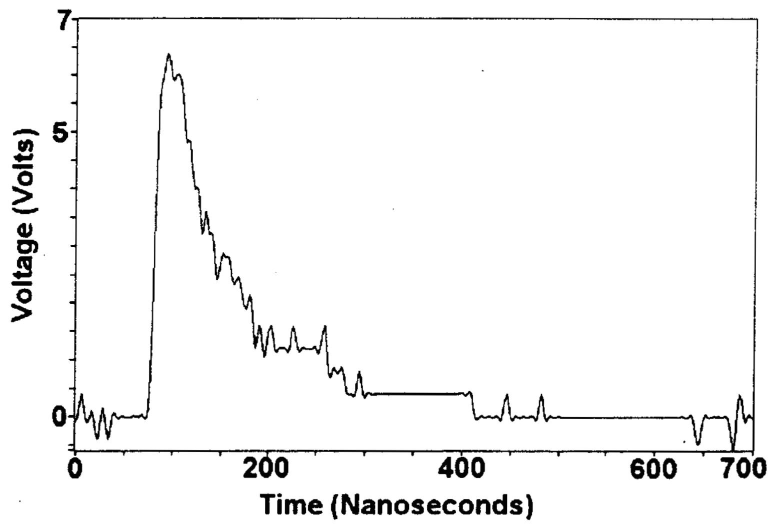

Figure 3. . FR4 circuit board sample #1, 7/12/99-4.43.28, 30 kV beam, 1 nA/cm2, 20 db attenuation (Vx10). Peak discharge current of 1.2A. Total discharge approx. 0.06 microcoulombs.

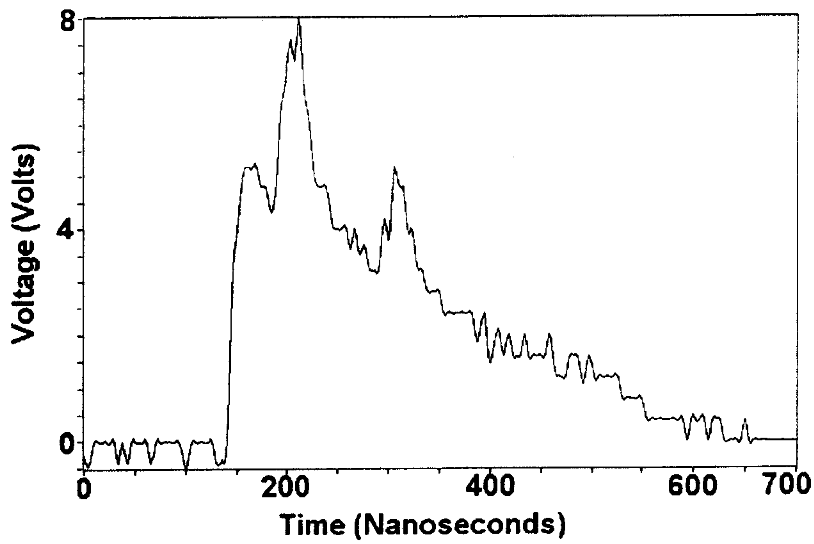

Figure 4. . FR4 circuit board sample #1, 7/12/99-4.45.28, 30 kV beam, 1 nA/cm2, 20 db attenuation (Vx10). Peak discharge current of 1.6A. Total discharge approx. 0.28 microcoulombs.

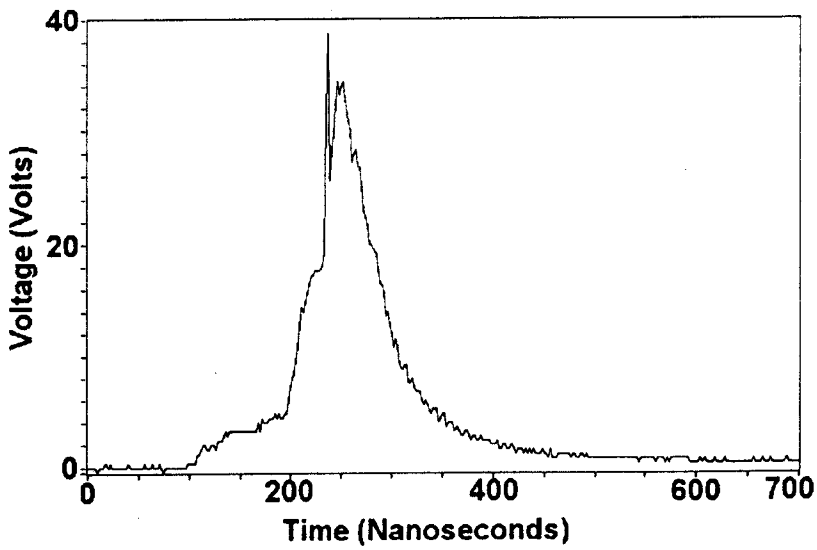

Figure 5. FR4 circuit board sample #1, 7/16/99-11.40.17, 30 kV beam, 1.8 nA/cm2, 30 db attenuation (Vx33). Peak discharge current of 26A. Total discharge approx. 2.6 microcoulombs.

APPENDIX

Some examples of samples procured for testing.

Circuit board samples

From JPL

- P/N 10153544 – Cassini AACS AFCX.

- P/N 10155737 – Seawind engineering model interface board.
- P/N 10157625 – Cassini Accelerometer.
- P/N 10153530 – Cassini Printed wiring board assembly, remote terminal input/output unit (RTIOU).
- P/N 10139250 – Cassini .
- 3 boards (one populated with dummy electronic components for use as test boards), FR-4 material.
- 3 boards (one populated with dummy electronic components for use as test board, one with a ground plane at the back), polyimide material.

From Cirtect Co.

- Substrate is 2 mil GXN Teflon (Arlon); tin on front, tin lead plate on back, surface is solder mask over tin; application is high frequency, RF circuits >10 MHz.
- Board mounted on a Al block – substrate is Roger 3006 Duroid (a ceramic-filled alloy) bonded to Al palate. Board can be removed from Al by sitting on a hot plate of 350-400 F. Board is used for high power RF amplifier.
- Substrate 20 mil FR-4 epoxy material. A 2-layer board. 1 ounce copper deposited on each side. The via are made of tin-lead.
- Substrate is GXN of 20 mil thick. Surface is copper traces coated with tin-lead instead of just tin. Both front and back are tin-lead.
- Roger 3006 material, 25 mil thick, with 1 ounce copper on surface.
- GXN material (Arlon), 19 mil thick, with 1 ounce copper on surface.
- Gil polyimid (Arlon), 20 mil thick. With 1 ounce copper on surface, Good for wide temperature variations.
- GFG, 10 mil thick, with 1 ounce copper on surface.

From Valley Circuits Co.

Quantity	Material	Type
1	Polyamide	059 1/1
6	GF	059 H/H
1	GF, 4 layers	093 1/1
1	Epoxy	2-sided 1/1
3	Epoxy	2-sided, 059 1/1
3	Polyamide, 10 layers	H/H

From NVF Co.

Four samples of the following circuit board material were tested 7/799 through 7/16/99 . The first test involved plain board material. In the second test 3 of the samples had some materials stuck on the uncladded side of the boards to minimally simulate the effects of components. The components enhanced the rate of discharge pulsing.

- FR-4 laminate made with epoxy resin and continuous filament woven glass fabric reinforcement.
- Thickness: 0.062"
- Sample size: 3"x3"
- Copper cladding: 1 oz copper foil on one side.
- Dielectric breakdown (parallel to lamination): 55kV
- Electric strength: 1200 V/mil

Sample	Attached material (pulse enhancer) on uncladded side
1	Copper tape 1"x1"
2	Cellophane tape 1"x3/4"
3	Square metal paper clip
4	No attachment

From Arlon Co.

Lot #	Thickness	Type	Assembly #
221465	0.0050	C1/C1	31G
221325	0.0100	C1/C1	31E
220940	0.0200	H1/H1	31
217048	0.0200	CH/CH	85G
221254	0.0050	C3/C3	85G
221145	0.0120	CH/CH	85G
092760	0.0060	C1/C1	63G
220478	0.0100	C1/C1	63G
221257	0.0050	H2/H2	45G
221298	0.0200	H1/H1	45G
221334	0.0120	C1/C1	45G
220248	0.0120	CT/CT	85T
221143	0.0050	H1/H1	85T
220480	0.0250	P1/P1	85T
220139	0.0060	HH/HH	55T
219082	0.0060	HH/HH	55RT
219070	0.0100	P1/HH	55T
216413	0.0200	HH/HH	55T
217239	0.0200	H1/H1	55RT
210019	0.0120	HH/HH	33G
216978	0.0120	C1/C1	35G
213101	0.0200	C1/C1	63G
219077	0.0050	C1/C1	33G
221152	0.0200	CH/CH	33G
221450	0.0280	C1/C1	35G
221456	0.0060	C3/C1	35G

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